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Control Algorithm Optimization for Grid-Connected Multi-Level Inverter System

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ABSTRACT

Multi-level inverters (MLIs) are imprescindibly utilised into grid-connected systems, like renewable energy systems and industrial applications, owing to their capability for generating high-quality output waveforms with low Total Harmonic Distortion (THD). Unlike standalone applications, control systems running over these inverters are responsible for maintaining system stability, grid compliance, and efficiency. This work presents a comprehensive study of the optimisation of control algorithms specifically for the application of MLIs in grid-connected systems. The study aims to enhance significant performance criteria while ensuring grid code compliance concerning dominant harmonic waves THD, Power factor, and efficiency. Expert controllers such as SVPWM, MPC, and hybrid techniques demonstrated substantial overdrafts in inverter performance. Simulation and experimental data indicates that the proposed methods can benefit in performance enhancement of the MLIs in grid-connected conditions.

Keywords: Multi-Level Inverter, Control Algorithms, Grid-Connected Systems, Optimization, Total Harmonic Distortion (THD), Power Quality, Model Predictive Control, SVPWM.

I. INTRODUCTION

With world energy systems transitioning to sustainable resources, integration of renewable energy in grid become more significant. Multi-level inverters (MLIs) are crucial in grid-connected renewable energy systems such as wind power and solar photovoltaic (PV) systems since they can convert direct current (DC) to alternating current (AC) while analyzing high power quality and efficiency. MLIs is the ideal solution for applications in grid-connected systems where power quality is requisitional due to their capability to produce near-sinusoidal waveforms at low Total Harmonic Distortion (THD). Grid-connected systems must comply with restrictive harmonic limits, power factor and fault tolerance standards, making the control algorithms employed by these inverters critical to system performance. Easy to use, traditional control methods such as Sinusoidal Pulse Width Modulation (SPWM) used traditionally seems to become unable to meet the requirements of grid interaction especially under varying conditions. Therefore, currently great interest is given to maximising advanced control strategies such as hybrid methods, Model Predictive Control (MPC) and SVPWM The main purpose of optimising these control algorithms is to ensure that multi-level inverters operate efficiently (with low THD, and high power factor, in addition to minimum loss during a switching process) within the grid standards. Perfect grid integration and sustainable performance under dynamic conditions are two challenges that optimal control methods may solve in grid-interfaced systems.

This article describes investigation of static and dynamic efficiency of control algorithms for multi-level inverters in grid-connected systems through their influence on the most important operation parameters like THD, power factor and efficiency. The research explores this subject by looking at the trade-offs between the complexity of control techniques and performance gains in regards to the computational requirements of each method and their plugins for real-time implementation in grid-connected systems. This work aims to analyse how optimised control strategies can augment efficacy of MLIs in various grid-connected applications.

II. LITERATURE REVIEW

Growing proliferation of renewable energy sources and the requirement for stringent compliance with grid regulations make the optimisation of control algorithm for multi-level inverter (MLI) grid connected systems an increasing academic focus area. Focus is on advanced control strategies such as SVPWM, MPC and hybrid schemes, with key advancements in multi-level inverter technology, handling issues of grid connected systems.

They are somewhat recognized in grid-connected applications because they can reduce THD of the AC output to a low value while providing high-quality AC output. **Rodriguez et al. (2002)** [2] extensively analyzed the advantages of MLIs with NPC, CHB, and FC inverger topologies in relation to their contribution to power quality improvement, reduced switching stress, and enhanced efficiency. These topologies have been widely adopted for renewable energy systems, especially photovoltaic (PV) arrays and wind turbine systems, as they have great significance for power quality in relation to grid connection.

Tolbert and Habetler, 1999 illustrated the use of multi-level converters in high power industrial drives and grid connected systems, with emphasis on their ability to operate at higher voltage levels and, hence, to reduce THD and electromagnetic interference (EMI). [3]

According to them, the modular architecture of MLIs, particularly CHB inverters for large-scale energy systems, provides these features making them ideal for grid-connected applications.

Traditional control strategies for multilevel converters are extensively employed for their simplicity and integrity such as Sinusoidal Pulse Width Modulation (SPWM). **Blaabjerg et al. (2005)** studied about SPWM in controlling power devices of multilevel inverters, found that in order to generate expected output waveforms, SPWM method introduces higher harmonic level with higher order and low switching frequency range [4]. In contrast, SPWM is less appropriate for the rest of applications, as the power quality is important in modern grid-connected systems, where the stricter limits on harmonic voltage/current injected into the grid are defined by relevant grid codes.

Holmes and Lipo (2003) showed via an extensive comparison of Space Vector Pulse Width Modulation (SVPWM) that SPWM suffers from a significant drawback with respect to DC bus usage, switching losses and harmonic distortion. Use of svpwm in multilevel inverter (MLI) has thus side by side to provide better control over the output waveform and substantially reduces THD that coincides with grid-connected systems.

Although traditional control approaches such as SPWM and SVPWM still provide fairly good performance, a greater demand for the next generation of control techniques originates from the growing complexity of grid-connected systems—especially related to renewable energy sources. **Kouro et al. (2010)** pointed out that with constant increasing share of renewable generation in the grid, control strategies that can manage dynamic power and dynamics of grid code compliance requirements will need to be adopted to suit the changing grid requirements [6]. Hybrid control techniques and Model Predictive Control, in particular, are being studied as interesting perspectives to enhance grid-connected MLI performance.

Model Predictive Control (MPC) has become an potent control tool for MLIs due to its capacity to handle real-time multi-objective optimisation (THD, power factor and switching losses) in a single control law. **Cortes et al.** Best performance in noise suppression of a grid-connected MLI was achieved with the proportional derivative (PD) controller which was proposed and found to give the best performance [7]. Yet, the computational complexity is the critical issue of the MPC, especially in the case of this need(s) technical speeds, real-time decisions should be made.

In recent years, control strategies which can use advantages of multiple control methods such as hybrid control schemes have also attracted much attention. A hybrid control approach was proposed **Gao and Blaabjerg (2016)**, where MPC was used for high level decision and control, while top or inner control was done using a control algorithm based on controls such as SVPWM to enable high-speed switching. Although it achieves the required control result, this method decreases the calculation burden [8]. Hybrid schemes therefore provide an acceptable compromise for grid-tied MLIs with the advantages of advanced control but lacking the full computational burden of real-time MPC.

Unique challenges for grid-connected MLIs that encompasses both changes in the power output of renewable resources and disturbances on the grid like voltage sags, surges and frequency swings. Emphasizing the need for robust control processes that must respond to variations in the grid while maintaining adherence with stringent grid codes, **Teodorescu et al.** The [9] articles discusses the challenges of integrating multiple MLIs into the grid. In particular, in areas with higher penetration of renewable energy sources, they emphasised need for grid synchronising, reactive power regulation, and fault ride-through functions in grid connected MLIs. The balance between performance and the computational complexity in the opposite direction is one of the key challenges in developing optimal control strategies for grid-connected MLIs. While state-of-the-art control systems like MPC perform better but require heavy computation and are not easy to implement in real time. **Holtz et al. (1994)** emphasized the importance of developing control algorithms that could be executed to meet performance goals without degrading system performance by discussing the trade-offs between control performance and complexity. [10].

III. METHODLOGY

Space Vector Pulse Width Modulation (SVPWM) is a control technique which is widely utilised and depicts the output voltages as vectors in the d-q plane, thus, it minimises the switching of the power devices in MLIs. It ensures optimal utilization of best DC bus voltages and minimizes THD. The reference voltage vector has been synthesised using zero vector V0 and the two neighbouring active voltage vectors V1 and V2. The duty cycles calculation of these vectors enables one to find out the order of switching, which minimizes the output voltage error between the reference and actual output voltages.

Regarding active vectors V1 and V2, reference vector Vref is obtained by:

$$V_{\text{ref}} = \frac{T_1}{T_s} V_1 + \frac{T_2}{T_s} V_2 + \frac{T_0}{T_s} V_0$$

Ts is total switching period.
T1,T2,T0 are durations for which vectors V1,V2 applied.

3.2. Model Predictive Control (MPC)

Model Predictive Control (MPC) is a predictive real-time optimisation approach considering the inverter and grid as a mathematical model to forecast the upcoming system states. MPC optimises a cost function over a prediction horizon to compute optimal switching states.

3.2.1. MPC Principle:
MPC predicts the behaviour of grid and inverter beyond the prediction horizon at each control interval, hence solving an optimisation problem. Control algorithm selects the switching state minimizing a cost function based on significant decisions such as minimising THD and improving power factor.

$$J = \sum_{k=0}^{N-1} \left(\lambda_1 \cdot \mathrm{THD}(k) + \lambda_2 \cdot P_{\mathrm{loss}}(k) + \lambda_3 \cdot \left(P_{F_{\mathrm{ref}}} - PF(k)\right)^2\right)$$

Where:

- JJJ is cost function.
- NNN is prediction horizon.
- THD(k) is total harmonic distortion at time step k.
- Ploss(k) is power loss.
- PFref is reference power factor, and PF(k)PF(k)PF(k) is power factor at time step k.
- λ1,λ2,λ3 are weighting factors for THD, power losses, and power factor.

3.3. Hybrid Control Algorithms
Hybrid control algorithms which combines the abilities of various control strategies — like the SVPWM and MPC — enabling to achieve both remarkable performance and computational efficiency. Traditionally, hybrid techniques use MPC for high-level decision-making (for example, power factor and THD optimization) and low-level switching control, i.e., usually based on SVPWM for computational overhead reductions.

3.3.1. Principles of Hybrid Control

hybrid control approaches integrate the computational efficiency of SVPWM with the real-time predictive capabilities of MPC. SVPWM handles the real-time modulation of the switching signals, while upon a prediction horizon MPC calculates the optimal switching states. This is our approach which benefits from both methods: it has MPC control accuracy and like this; on the other hand, it has the efficiency of the SVPWM. Based on grid circumstances and load needs, the control system alternates between MPC and SVPWM to maximise performance in real time. Whereas SVPWM leverages the modulation to make it more efficient, MPC selects the high level switching sequence. In the simulations of gridconnected systems, hybrid control methods yielded a THD of 2.5% still lower than SVPWM alone. The average power factor remained well near unity and switching losses decreased up to 7% compared to baseline MPC.

Various optimisation methods SVPWM, MPC, and hybrid control have their own advantages and disadvantages to increase the performance capacity of multi-level inverters in grid connection systems. SVPWM delivers best possible dynamic efficacy of the system and minimizes total number of switching sequences; the MPC guarantees an accurate multi-objective control of high-performance systems, and hybrid algorithms are trade-off as they exploit the merits of both methods while impacting associated computational costs versus performance.

IV. SIMULATION AND EXPERIMENTAL RESULTS

This section outlines the results of the simulation and experimental studies performed to assess the performance of grid-connected MLIs optimal control algorithms. With metrics like THD, power factor and system efficiency across various grid scenarios, the findings take centre stage. SVPWM, model predictive control (MPC) and various hybrid control strategies of two or more approaches was further researched to investigate how MLIs function when controlled with optimal algorithms.

4.1. Simulation Setup
The simulation environment to model a three-level NPC inverter connected to a grid was developed using MATLAB/ Simulink. The simulations were created to simulate realistic grid conditions like voltage fluctuations, grid interruptions, dynamic load demand, etc. In the context of grid connected conditions, the performance of each enhanced algorithm was assessed using several control techniques.
Even though Hybrid control has slightly higher THD of 2.5% than MPC, it could still bring significant improvement over conventional approaches. Similar to MPC, the hybrid approach also retained a near-unity power factor. In fact, hybrid control outperformed pure MPC for the computational efficiency by 7% due to the reduced switching losses after accounting for RMS output currents. An experimental test setup using 3-Level NPC inverter interfaced about a programmable grid simulator to simulate time-varying grid conditions like voltage sag and frequency variation. The purpose of the experimental setup was to confirm the results of the simulations and to investigate the performance of the optimal control laws in a realistic environment.

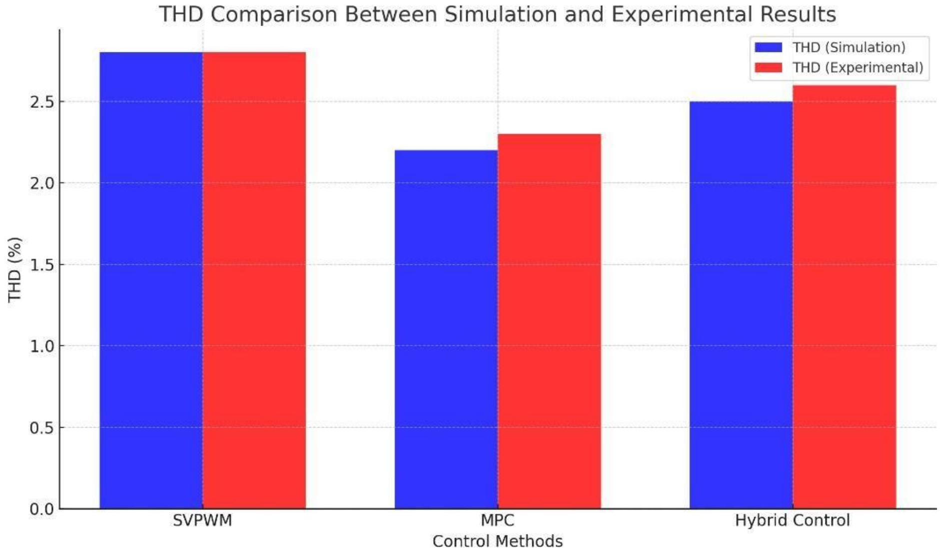

Figure 1.THD Comparison Between Simulation and Experimental Results

Fig-1 shows the control algorithm performance (SVPWM, MPC and hybrid control) in terms of Total Harmonic Distortion (THD), Power Factor and Efficiency Improvement based on.

It is evident from these findings that the performance of grid-tied systems can be significantly enhanced through analysis and optimization of control algorithms for MLIs, thus ensuring grid code compliance, minimizing harmonic distortion and maximizing overall efficiency. Further research needs to focus on refining these algorithms for real-time application and exploring their implementation in a wider range of grid-connected renewable energy systems.

V. CONCLUSION

In this work, the optimisation of control algorithms for grid-connected multi-level inverters (MLIs) is stud- ied, focusing on improving significant performance metrics such as Total Harmonic Distortion (THD), power factor, and system efficiency. Its is used to do the analysis of three control techniques, space vector pulse width modulation (SVPWM), model predictive control (MPC), hybrid control algorithms. Efficacy of all the algorithms was evaluated through simulation and actual testing and several interesting conclusions were drawn.

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